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J. Ge, D. Ciarlo, P. Kuzmenko, C. Alcock, B. Macintosh,
R. Angel, N. Woolf, M. Lloyd-Hart, R.Q. Fugate and J. Najita

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Adaptive Optics High Resolution Spectroscopy: Present Status and Future Direction[1]

Jian Ge, D. Ciarlo, P. Kuzmenko, C. Alcock, B. Macintosh
Lawrence Livermore National Laboratory, Livermore, CA 94551

R. Angel, N. Woolf, M. Lloyd-Hart
Steward Observatory, University of Arizona, Tucson, AZ 85721

R. Q. Fugate
Starfire Optical Range, Directed Energy Directorate, Air Force Research Laboratory, Kirtland AFB, NM 87117

J. Najita
National Optical Astronomy Observatories, Tucson, AZ 85726

Abstract

High resolution spectroscopy experiments with visible adaptive optics (AO) telescopes at Starfire Optical Range and Mt. Wilson have demonstrated that spectral resolution can be routinely improved by a factor of ~ 10 over the seeing-limited case with no extra light losses at visible wavelengths. With large CCDs now available, a very wide wavelength range can be covered in a single exposure.

In the near future, most large ground-based telescopes will be equipped with powerful AO systems. Most of these systems are aimed primarily at diffraction-limited operation in the near IR. An exciting new opportunity will thus open up for high resolution IR spectroscopy. Immersion echelle gratings with much coarser grooves being developed by us at LLNL will play a critical role in achieving high spectral resolution with a compact and low cost IR cryogenically cooled spectrograph and simultaneous large wavelength coverage on relatively small IR detectors.

We have constructed a new AO optimized spectrograph at Steward Observatory to provide R = 200,000 in the optical, which is being commissioned at the Starfire Optical Range 3.5m telescope. We have completed the optical design of the LLNL IR Immersion Spectrograph (LISPEC) to take advantage of improved silicon etching technology.

Key words: adaptive optics, spectroscopy, high resolution, immersion gratings

1. Introduction

Very high-resolution optical and infrared spectroscopy is one of the most exciting new fields to be explored in astronomy. Its major applications include search for newly formed extra-solar planets (Carr & Najita 1997) and extra-solar planets around old stars (Marcy & Butler 1998), and the study of the structure, physics and chemistry of proto-planetary and planet forming circumstellar disks. It also offers unprecedented sensitivity for study of stellar magnetic fields, interstellar and circumstellar medium, stellar abundance and isotopic abundance.

Despite the tremendous potential of very high resolution optical and infrared spectroscopy to provide major breakthroughs in astronomy, it was very difficult to achieve because of lack of efficient techniques (Ge 1998). Adaptive optics correcting telescope wavefront errors caused by the atmospheric turbulence and

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[1] Send correspondence to Jian Ge, email: ge1@llnl.gov

restoring diffraction-limited images however has the potential for very high resolution spectroscopy in an efficient way for the first time. For a well corrected telescope, the spectral resolution can be potentially increased by a factor of D/r_0 where r_0 is the atmospheric coherence length and D is the telescope aperture size. At a good seeing site, $D/r_0 \sim 10$ in the near IR for a 8m telescope and in the optical for a 2m telescope.

Current adaptive optics systems being developed will provide high order wavefront correction in the IR for 8m class telescopes. The same adaptive optics systems will be able to correct wavefront errors in the optical for 2m class telescopes. Therefore, spectral resolution can be potentially boosted by a factor of 10 in the IR for large size telescopes and in the optical for medium size telescopes. Current state-of-the-art high spectral resolution in the optical and IR under seeing conditions is R ~ 30,000 (Suntzeff 1995). Therefore, the next generation high spectral resolution range with adaptive optics will be R ~ 300,000.

Optical adaptive optics spectroscopy experiments with a prototype spectrograph at the SOR 1.5m and Mt. Wilson 100inch telescopes demonstrated a spectral resolution of R ~ 250,000 in the optical (Ge et al. 1996a,b; 1998). This resolution is a factor of ten times higher than that provided by the same spectrograph operated under seeing conditions. To our knowledge this is the first time a high resolution spectrograph has been used with diffraction-limited images produced by AO systems. It demonstrated the expected advantage of good throughput and large λ coverage (Ge et al. 1996a,b; 1998; Ge 1998). Figure 1 shows the K I 7698 Å absorption spectra from the interstellar diffuse clouds toward bright stars ζ Persei (V = 2.8) and α Cygni (V = 1.3) with spectral resolution R ~ 250,000. The signal to noise ratio is 200 for α Cygni and 100 for ζ Persei. It also demonstrates the potential scientific capability with the AO high *R* spectrograph.

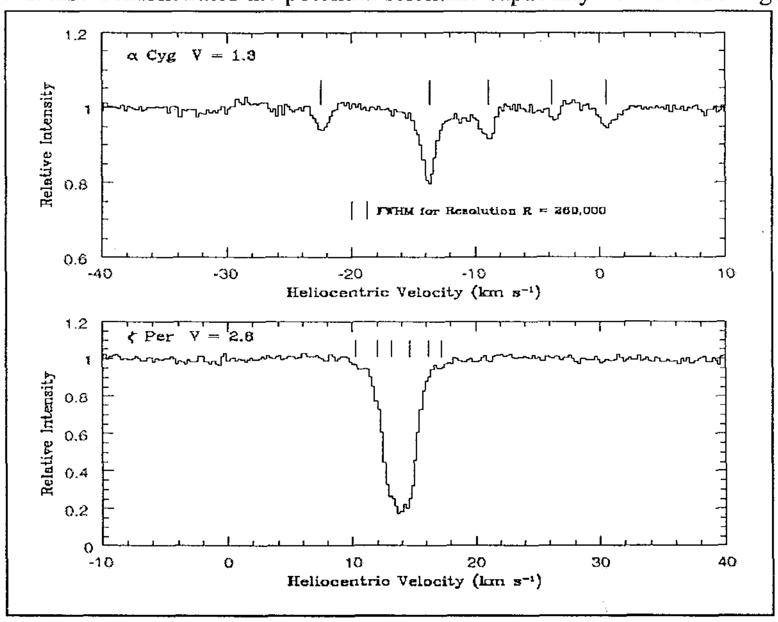

Figure 1. The interstellar K I λ 7698 Å absorption lines in the spectra of α Cygni and ζ Persei. The velocity components with strong K I absorption are marked (Ge 1998).

The Mt. Wilson AO spectroscopy experiment in November 1997 further demonstrated the suitability of a 10 μm near single mode fiber for transmitting AO corrected beams from the telescope to a bench-mounted high resolution spectrograph. The total throughput of the fiber coupling was ~ 65%. It further demonstrated large wavelength coverage of AO spectroscopy. A 1kx1k Apogee CCD detector with 24 μm pixel size covers about 80 cross-dispersed orders or ~ 700 Å wavelengths per exposure (Ge et al. 1998).

In this paper, we report the progress on a newly developed AO optimized high resolution optical spectrograph at Steward Observatory. We also report the progress on a compact IR high resolution spectrograph with silicon immersion echelle gratings being developed at LLNL. Because IR spectrographs have to be cooled to cryogenic temperatures to minimize thermal background, spectrograph size is the major constraint factor for the design of IR high resolution spectrographs. Special technique is required to reduce the spectrograph size. The most promising technique is to apply immersion gratings made of silicon to provide a factor of 3.4 increased spectral dispersion over conventional reflective gratings. Therefore, the total cryogenic chamber size for housing the spectrograph can be substantially reduced while the resolution is maintained, and the total cost is greatly reduced.

2. Optical cross-dispersed echelle spectrograph with R = 200,000

A new cross-dispersed optical echelle spectrograph has been constructed at Steward Observatory. This spectrograph is designed to collect AO corrected beams within 0.15″ aperture from a point source from the SOR 3.5m telescope through a near single mode fiber. It provides a resolution of R = 200,000 in 0.35-1.1 μm. Initial test of the spectrograph was conducted at Steward Observatory in November 1998. The test demonstrates its excellent performance.

Figure 2 shows the setup of the spectrograph mounted on a Newport optical bench at Steward Observatory in November 1998. The spectrograph focal length is 1.9 m and focal ratio is f/16. It is arranged in a near Littrow configuration. A novel Maksutov-type design is adopted to reduce the total construction cost. Instead of a slit, the spectrograph is fed with a 10 μm fused silica fiber. An input coupler with control in x, y, and tilt feeds the fiber at *f*/4. At the fiber output, another coupler converts the beam to *f*/16, with a corresponding magnification to an apparent entrance slit size of 40 μm. The spectrograph collimator and camera mirror is a 10 inch diameter sphere coated with protected silver. A Maksutov plate is used to correct coma and astigmatism. The main disperser of a Milton Roy R2 echelle with 250x125 mm^2 ruled area and the cross-disperser of a 21 deg BK7 prism are installed in a box for protection. The prism is applied in double path to increase cross-dispersion. Multi-layer anti-reflection coatings are used to the Prism and Maksutov plate to provide more than 98% transmission per surface over 0.35 to 1.0 μm.

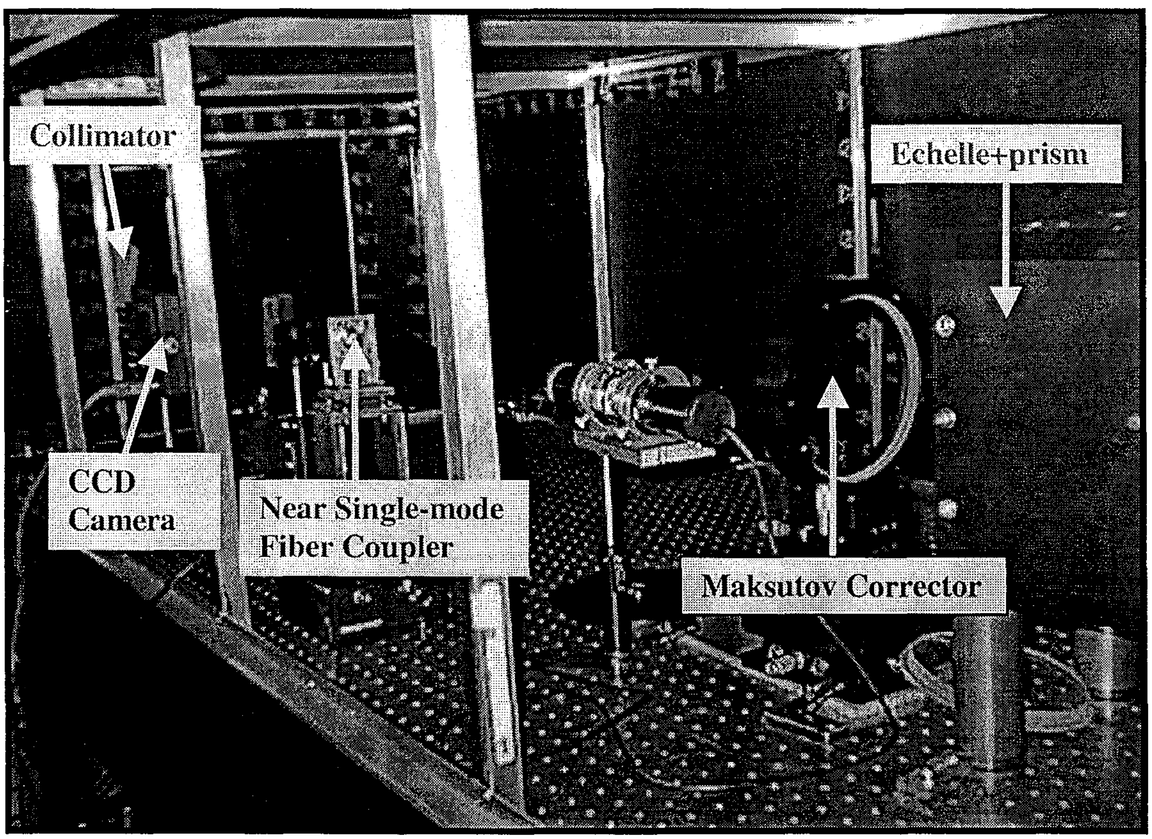

Figure 2. Setup of the new optical AO spectrograph at Steward Observatory in November 1998. It is being commissioned at the SOR 3.5m telescope.

A HeNe laser line at 6328 Å with this spectrograph shows a FWHM of 38 μm (1.6 Apogee CCD pixels), corresponding to R = 190,000 at the laser frequency (Figure 3). Because of the undersampling of the spectral resolution element with the Apogee CCD, a higher spectral resolution can be potentially achieved with a CCD detector with smaller pixels.

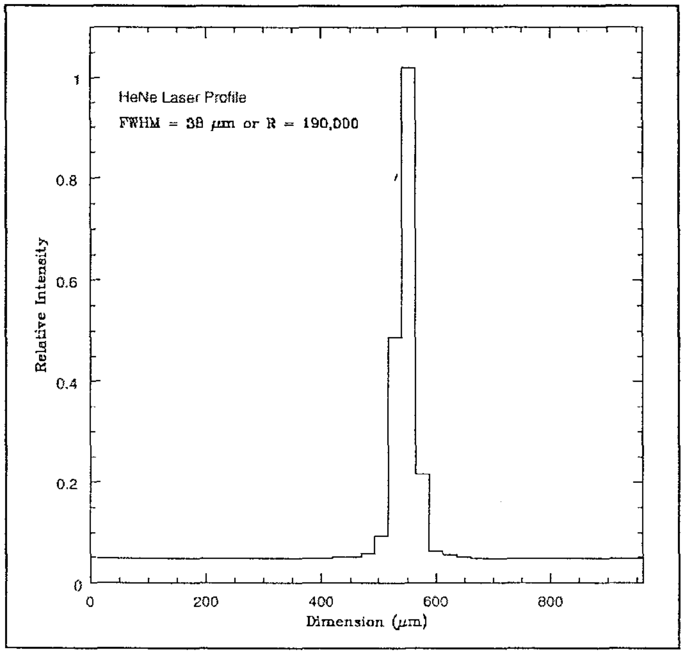

Figure 3. Spectral line profile of a HeNe laser at 6328 Å. It demonstrates a spectral resolution of R = 190,000.

The spectrograph has been further tested with sunlight in May 1999 by connecting it (in the lab) to a small electric star tracker on the roof of Steward Observatory. The detector is a 2k x 4k thinned Loral CCD with 15μm pixels newly constructed for scientific observations with this spectrograph. Part of a solar spectrum obtained with the spectrograph is shown in Figure 4. The cross-dispersed order profile shows the excellent order separation achieved with the diffraction-limited image from the fiber.

The close spacing of the orders allowed by the AO and the large area of the CCD means that about 100 orders (or 4000 Å) can be recorded simultaneously, providing in one shot almost complete spectral coverage across the entire range of wavelength to which the CCD is sensitive. This is crucial to the scientific goal of the projects to be conducted with this spectrograph . Unlike other seeing-limited spectrographs with similar spectral resolution, lines from the different stellar atmospheric layers can be imaged simultaneously, increasing efficiency and eliminating many instrumental effects caused by recalibration to a different waveband between exposures.

The spectrograph is being commissioned at the SOR 3.5m telescope. The first light of the spectrograph will be in August 1999. The overall total detection efficiency at the SOR 3.5m is expected to about 3%, a factor of three times higher than the prototype AO spectrograph used at the SOR 1.5m telescope due to the increased QE of the CCD detector (90% vs. 40%) and improved optics transmission in the spectrograph. Thus in 10 minutes integration, we expect to obtain spectra of V = 7 mag. stars with S/N = 200 per pixel at the SOR 3.5m.

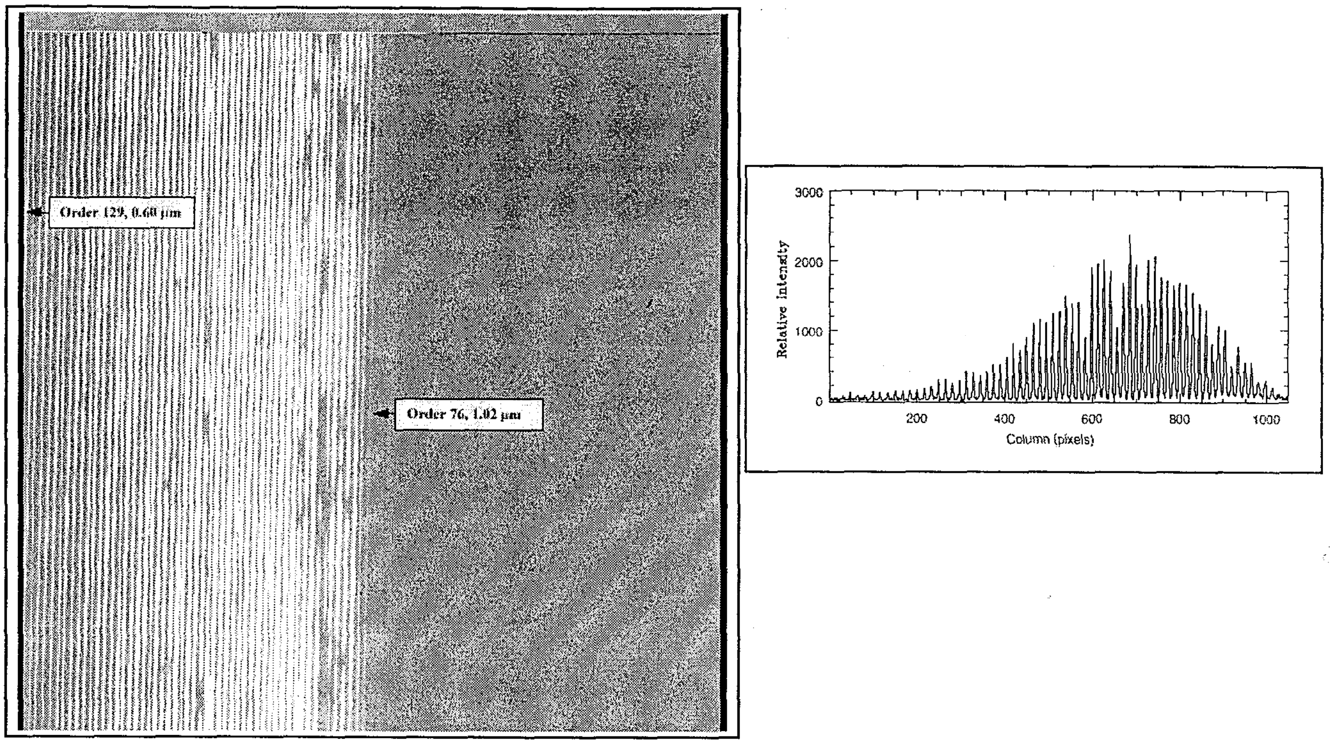

Figure 4. Part of a solar spectrum obtained with the spectrograph and a 2kx4k Loral CCD camera. The cross dispersed orders from 76 (or 1.02 μm) to 129 (or 0.60 μm) are covered in this figure. The camera can cover 100 cross-dispersed orders or 4000 Å from 0.5 to 1.0 μm in one exposure. The absorption features are telluric absorption lines in the red wavelengths. The cross-dispersed order profile demonstrates nearly homogeneous separations in the optical, with a minimum separation of 240 μm or 16 pixels in the long wavelength regions.

3. IR Cross-dispersed Echelle Spectrograph with *R* ~ 200,000

A compact IR high resolution cross-dispersed echelle spectrograph is being developed at LLNL. The spectrograph will be operated in 1.3-5.5 μm. A key element, the echelle grating, is made of silicon operated in immersion mode as shown Figure 5.

3.1. Silicon immersion grating development

The silicon immersion grating increases the spectral dispersion power by a factor of 3.4 over that of a conventional reflective diffraction grating of equal length. Several groups have worked on etching silicon gratings and have achieved a measure of success with thin wafers (e.g. Wiedemann et al. 1993; Kuzmenko et al. 1994, 1998; Jaffe et al. 1998). However, a true immersion grating, where the etched surface is on the hypotenuse of a prism, requires the processing of thick pieces of silicon and is much more problematical. No one has yet produced a silicon immersion grating of high enough quality to be useful for high resolution spectroscopy.

We continue our development of silicon immersion gratings in the Microtechnology center at LLNL. New combination of techniques to overcome previous problems and improve immersion grating quality are being and will be applied to make them useful for spectroscopic applications (see Kuzmenko & Ciarlo 1998, 1994 for technical details). The new techniques include:

- Hot phosphoric acid to pattern the silicon nitride etch mask prior to the KOH etching of the silicon
- Ultrasonic agitation during the KOH chemical etching to break free the hydrogen bubbles and reduce the roughness of the etched grating facets
- Photoresist deposition by meniscus coating and/or electrodeposition for lithography on thick, heavy silicon disks

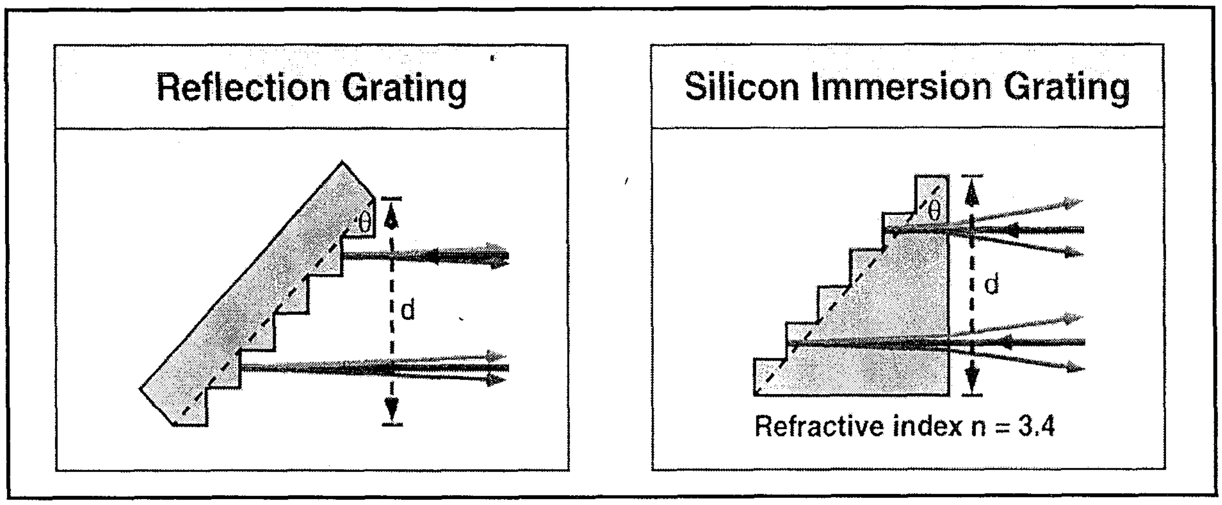

Figure 5. Comparison between a traditional reflective grating and a silicon immersion grating. The silicon immersion grating increase the spectral dispersion by a factor of 3.4 times.

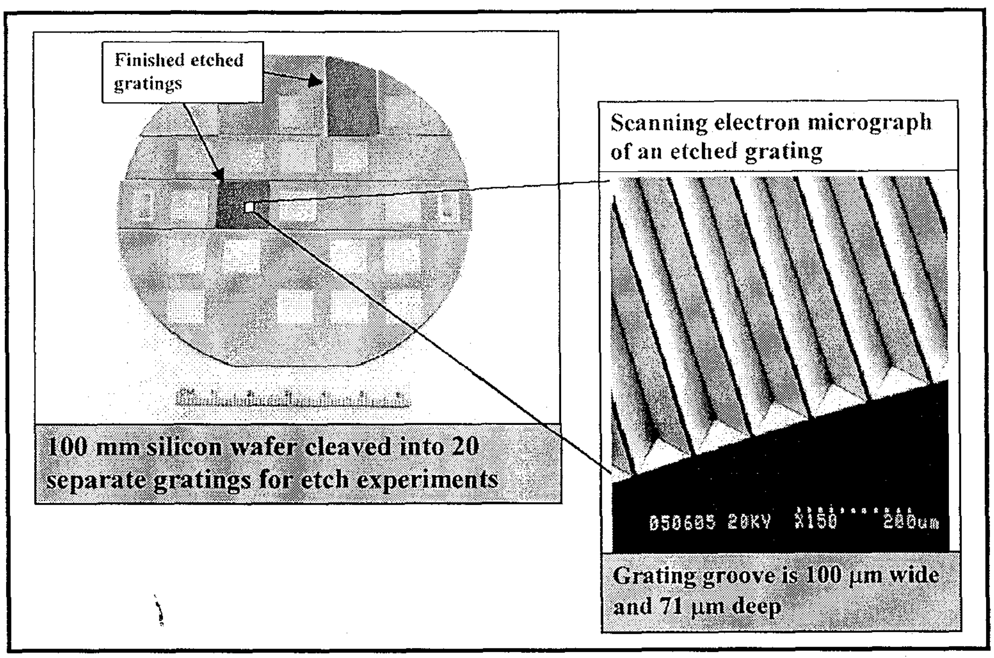

Figure 6. 10x10 mm^2 testing gratings are etched on a silicon wafer for testing new techniques at LLNL

Numerous experiments were conducted on 4-inch silicon wafers, each containing 20 diffraction gratings, 10 by 10 mm in size, as shown in Figure 6. Some of the conclusions from experiments to this date are as follows:

- The thermal oxidation system used for our 4-inch wafers deposits oxide with a variable density over the wafers surface. This results in grating defects because of excess lateral etching during the fabrication (Figure 7)

- The plasma etcher used to etch our silicon nitride wet etch mask causes a scarring of the silicon surface under the nitride. This scarring is then transferred to the (111) grating facets leading to a roughened surface

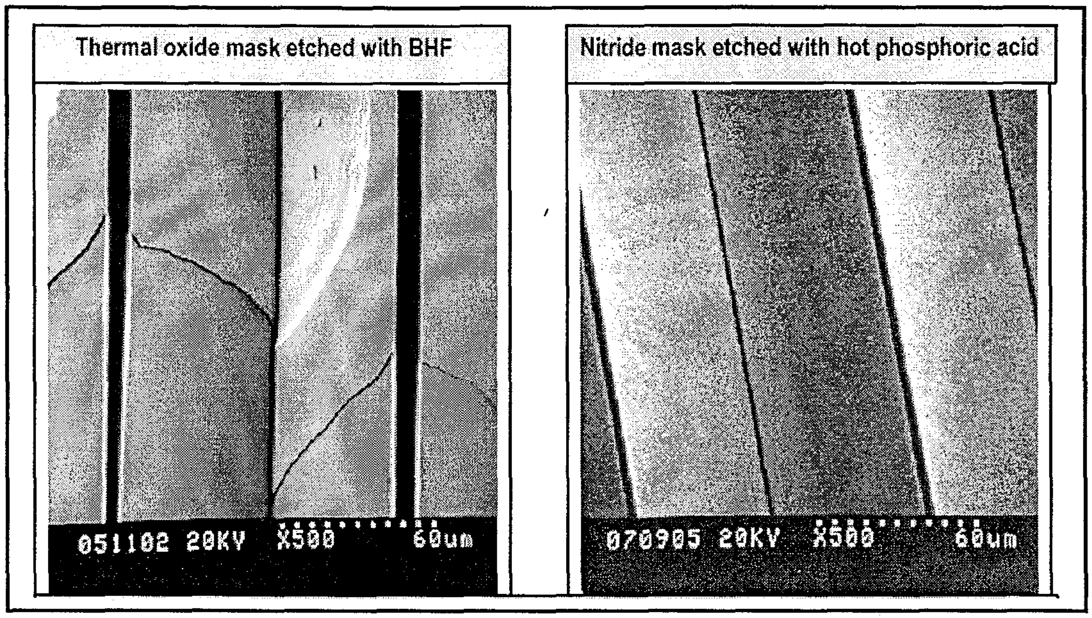

Figure 7. Comparison between the eched gratings with different process (thermal oxide mask with Buffered Hydrofluoride Acid (BHF) vs. nitride mask with hot phosphoric acid). Hot phosphoric acid process eliminates "shingle" and "scallop" defects over area of 10x10 mm^2 and is being applied to silicon with much large surface area.

Both of the problems can be potentially solved with further experiments. However, we chose to use hot phosphoric acid to pattern the silicon nitride etch mask prior to the KOH etching of the silicon. A re-flux unit was set up so that the acid could be heated to 160° C. At this temperature the nitride etches at a rate of 50 Å/min. It is patterned using a chrome/gold metal mask. Initial results with this system are encouraging (Figure 7).

- The silicon under the nitride remains highly polished
- There are very few scallops or shingle defects in the etched gratings
- This process is very compatible with the use of thick silicon disks
- The smoothness of the (111) grating facets is now being measured

We have been collaborating with researchers at Univ. of Texas to etch gratings under ultrasonic conditions. In addition, we have started working on larger area gratings, 40 by 60 mm, still on thin silicon wafers. Thick silicon disks will be used once we finish the experiments with the wafers. We expect to have several prototype silicon immersion gratings for testing by the end of this year.

3.2. Design study of silicon immersion spectrographs

A prototype IR spectrograph with the silicon immersion echelle has been designed and shown in Figure 8. A silicon grating with 100x50 mm^2 etched surface is planned to be used in this prototype to provide R ~ 200,000 in the near IR. The spectrograph size is about 1m long, 0.5m wide and 0.5m high. It will be operated without cooling, only 1.3-1.8 μm wavelength will be observed, where thermal background is negligible. An off-axis parabola provides spectrograph beam collimating and camera focusing. A silicon prism with a wedge angle of 24 degree operated in double pass mode will provide cross-dispersion. An existing near-IR camera with a 256x256 HgCdTe array will be used for recording spectra. The minimum order separation is about 13 pixels (or 500 μm). The IR array will cover ~ 20 cross-dispersed orders or 200 Å in one exposure. The spectrograph will be coupled with the Lick 3m telescope through a single mode fiber with core diameter of 10 μm to take advantage of its adaptive optics corrected diffraction-limited images. This fiber will accept 0.2″ telescope AO beams at *f*/4, within which ~ 50% photons from a point source will be collected. The total detection efficiency is about 4% at the Lick 3m. Thus in one hour integration, we expect to obtain spectra of H = 8 mag. stars with S/N = 150 per pixel. This prototype will be constructed this fall and initial scientific observations with it at Lick will start shortly after that.

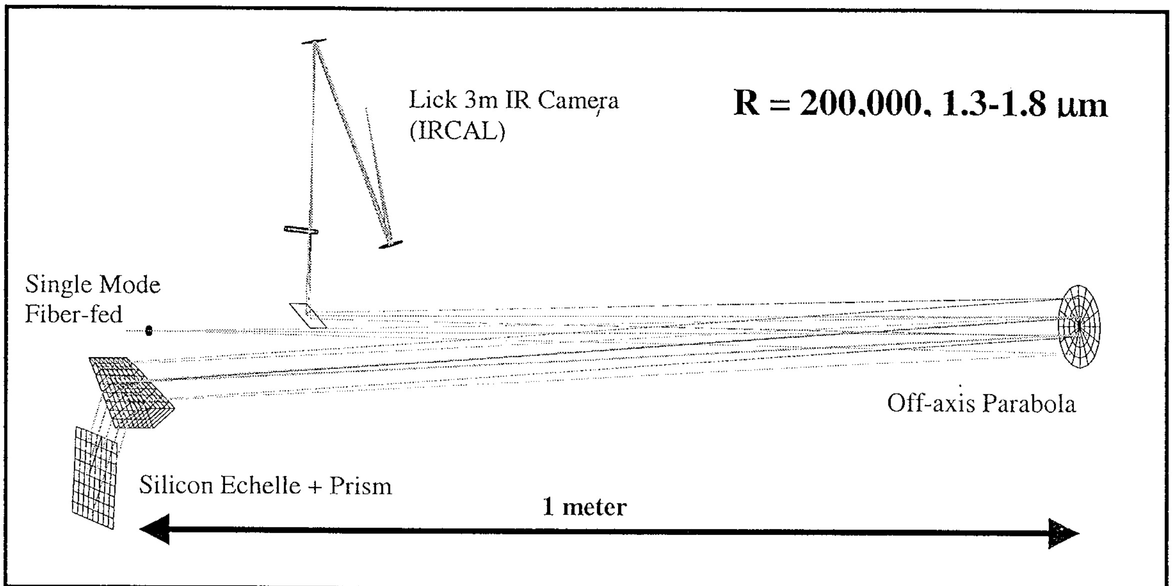

Figure 8. Optical layout of the prototype IR immersion spectrograph with R = 200,000 in 1.3-1.8 μm. An off-axis parabola with focal length of 1.0 m is used as the collimator and camera mirror. A silicon immersion echelle and a silicon prism provide dispersion and cross-dispersion, respectively. An existing 256x256 IR camera is used for data collection.

Table1. Summary of LISPEC Specification at Lick 3m telescope

Detector	HgCdTe (MBE), 18.5 μm pix
Wavelengths	1.3-5.5 μm
Focal ratio	f/12.6
Plate scale	0.1 arcsec/pixel
Slit size	0.2 arcsec
Grating constant	33.3 grooves/mm
Spectral Resolution (Immersion echelle with 63.5 deg blaze angle)	240,000
Physical size of free wavelength range on detector at 2.2 μm (order 83)	103.4 mm
Detector dimension (1kx1k)	18.9x18.9 mm

Our ultimate goal is to develop a cryogenic version of very high resolution IR immersion spectrograph to cover from 1.3 to 5.5 μm broad wavelengths. This cryogenic version of the spectrograph is called LLNL IR Immersion Spectrograph (LISPEC). LISPEC is a compact and portable instrument. It will be initially used at the Lick 3m telescope and later used at such as Keck II and Gemini telescopes. Figure 9 shows a preliminary design of LISPEC. The design is very similar to that of Arizona IR Imager and Echelle Spectrograph (ARIES) (see McCarthy et al. 1998; Ge 1998; Sarlot et al. 1999). An Offner optics reimages a telescope Cassegrain focus to a more convenient location as well as provide a "cold" pupil on its secondary for thermal baffling. An off-axis parabola collimates the beam from the Offner optics and forms a second pupil inside the dewar, where a silicon prism is located. The silicon wedge prism operated in double pass provides cross-dispersion, while the silicon immersion echelle provides main spectral dispersion. The dispersed beams pass three-mirror camera system and form spectra on an IR detector. The detector is likely to be a MBE processed 1kx1k HgCdTe array with 18.5 μm pixel size.

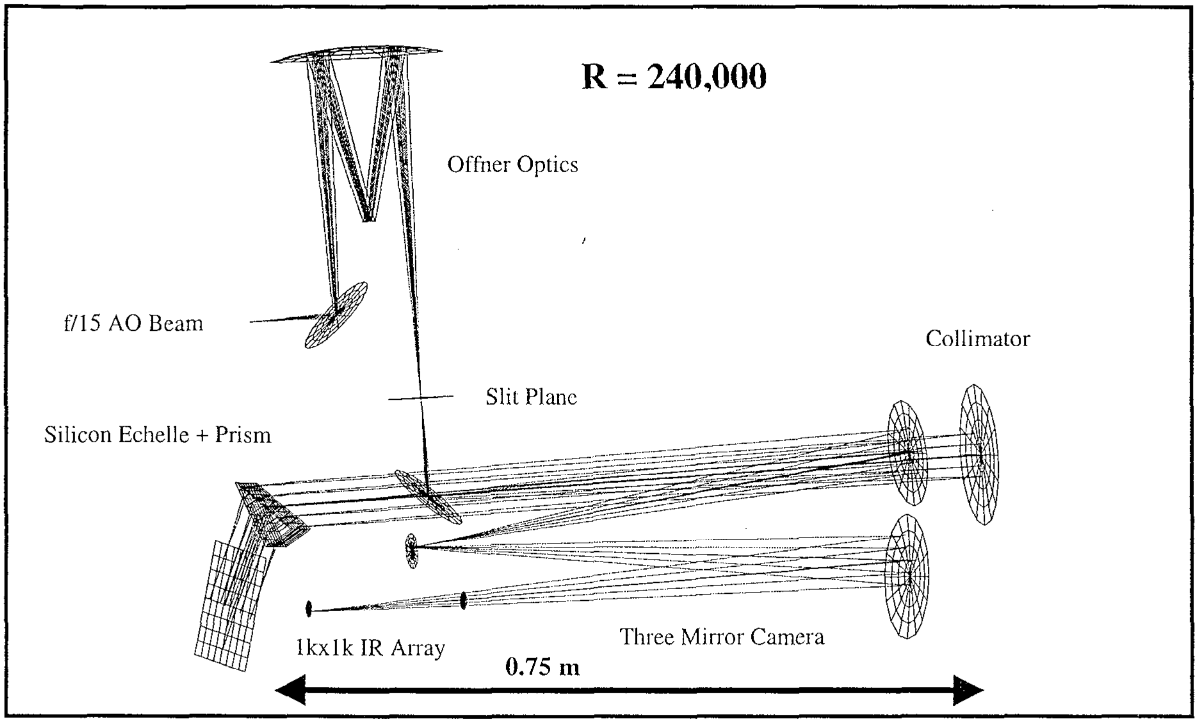

Fig. 9. Optical layout of LISPEC: a f/15 AO beam forms a cold pupil on the secondary of the Offner optics, an off-axis paraboloid collimates the f/15 beam and forms a second pupil on the prism which provides cross-dispersion. The dispersed beams from the immersion echelle and prism form spectra on a 1kx1k HgCdTe array by a three-mirror camera system with effective focal length of 630 mm.

The design results show that a silicon immersion echelle with 63.5 degree blaze angle and 50 mm collimator beam at f/12.6 is able to provide spectral resolution R = 240,000 at 1.3-5.5 μm at the Lick 3m telescope with adaptive optics. This spectral resolution, close to its potential diffraction-limited one, is a factor of four times that provided by the Phoenix IR spectrograph, the current highest spectral resolution spectrograph in astronomy (Hinkel et al. 1998). The silicon prism cross-disperser with 24 degree wedge angle packs about 50 relatively short orders on the 1Kx1K IR array to provide a wavelength coverage of 0.2 μm in one grating setting. If a *f*/6.3 lenses is inserted between the IR array and the last mirror of the camera, R = 120,000 and 0.4 μm coverage will be obtained. Table 1 further lists LISPEC specifications at the Lick 3m telescope.

This spectrograph has been designed to have diffraction-limited optical performance at 2.2 μm over 100 arcsec field of view, so it can be used for direct imaging. This direct imaging mode is also served as a slit viewer for initial alignment of a scientific target with the spectrograph, which helps to significantly reduce total construction cost. The optical design is close to be finalized and we are about to move to next phase of mechanical, cryogenic and electronic designs of the whole system. The first light of this spectrograph will be in 2002.

Acknowledgements

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